Catalogue no. 82-003-X
ISSN 1209-1367

Health Reports

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Release date: July 20, 2016

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^{p} preliminary
^{r} revised
x suppressed to meet the confidentiality requirements of the *Statistics Act*
^{E} use with caution
F too unreliable to be published
* significantly different from reference category ($p < 0.05$)

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Abstract

Background: Nitrogen dioxide (NO_2) is a marker for traffic-related air pollution, which exhibits strong spatial gradients in large cities. Previous studies have shown that in Canadian cities, exposure to ambient NO_2 is greater in neighbourhoods of low socioeconomic status (SES). As a result of these differences in exposure, air pollution-related health problems may be more prevalent among children in lower SES urban neighbourhoods.

Data and methods: Children younger than age 18 enumerated in the 2006 Census who lived in Toronto, Montreal or Vancouver were linked to published air pollution exposure land use regression models to assign exposure at the Dissemination Area (DA) level. Associations between both socioeconomic and visible minority status and exposure to ambient NO_2 among children in these three cities were examined in a series of regression models (OLS and simultaneous autoregressive models that account for spatial autocorrelation).

Results: Children in lower income DAs in all three cities were exposed to higher NO_2 concentrations than were children in higher income DAs (mean difference of 2 ppb between lowest and highest income quintiles). In some cities, DAs with larger percentages of children in lone-parent families and visible minority children were characterized by greater NO_2 exposure.

Interpretation: The relatively high incidence of air pollution-related diseases (for example, asthma) among children in lower SES neighbourhoods may be attributable, at least in part, to variations in NO_2 air pollution exposure within the same city.

Key words: Air pollution, asthma, environmental health, income quintile, nitrogen dioxide

Environmental exposure to nitrogen dioxide (NO_2), which is largely a by-product of vehicular exhaust and incomplete combustion of fossil fuels, has been associated with emergency hospitalizations for respiratory conditions among adults in lower income quartiles in large Canadian cities.[1] Researchers have hypothesized that children may be even more vulnerable to the effects of air pollution because of their greater susceptibility to respiratory damage and faster respiratory rate, both of which exacerbate the effects of exposure.[2,3] A time-series study of school-aged children in Vancouver observed that boys had a greater risk of asthma hospitalization after increases in ambient NO_2 exposure if they were of low rather than high socioeconomic status (SES).[2]

NO_2 exposure among children has been associated with an increased risk of asthma, wheezing, ear, nose and throat infections, influenza, and serious colds[4-7]; reduced lung function[8]; and more severe respiratory tract infections for those with asthma.[9] A California study found that each increase of 5.7 ppb in NO_2 exposure was associated with almost a doubling of asthma prevalence.[5] According to a similar Vancouver study, exposure to NO_2 increases of 10 $\mu g/m^3$ during the first year of life significantly increased the odds of developing asthma.[6] In addition to these health outcomes, air pollution exposure has been related to reduced school attendance and academic performance within the northeastern United States.[3]

Previous Canadian studies have reported significant within-city variations in residential exposure to NO_2 among adults,[10] and have correlated neighbourhood socioeconomic characteristics such as low income, lower educational attainment, and lower dwelling value with higher exposures.[10,11]

It is possible that NO_2 exposure varies within cities, and that children in lower income neighbourhoods have greater exposure than do those in higher income neighbourhoods.[2] The purpose of the present study was to determine if NO_2 exposure in the three largest Canadian cities—Toronto, Montreal, and Vancouver—was higher among children of lower SES and who were members of visible minorities.

Data and methods

Nitrogen dioxide exposure data were taken from published land use regression (LUR) models for Toronto, Montreal, and Vancouver, which had been created based on a combination of extensive field-measured samples of NO_2 along with datasets describing local land use characteristics, such as traffic counts, land use patterns, and population and road densities.[12-14] The Montreal LUR model pertains to mean annual concentrations in 2006. The Toronto and Vancouver NO_2 models were based on data from 2003 and 2010, respectively, and were adjusted with observations from Environment Canada's National Air Pollution Surveillance network to be consistent with city-wide mean values for 2006.[15] This adjustment for year is supported by analyses in Canada and Europe demonstrating that NO_2 spatial models are consistent over time.[14,16,17]

Socioeconomic, visible minority, and demographic data for children were derived from the 2006 Canadian Census long-form

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questionnaire, representing a random sample of 20% of the three urban populations.[18] Children were included in the study if they lived within the boundaries of the LUR models for Toronto, Montreal or Vancouver,[12-14] were younger than age 18, and did not live in an institution. The LURs do not include all the suburban communities in the greater Toronto area, or areas beyond the island of Montreal. The variables derived for each child were before-tax household income, residence in a lone-parent family, visible minority status, age, and sex. Visible minorities are persons (other than Aboriginal), who are non-Caucasian (race) or non-white (colour).[18]

Respondent data were aggregated to the Dissemination Area (DA) level. DAs consist of one or more Census dissemination blocks and have populations of 400 to 700.[18] A Geographic Information System (ArcGIS v.10, ESRI 2010) was used to map respondents to their approximate location of residence using Statistics Canada's Postal Code Conversion File (PCCF+) version 5K.[19] The PCCF+ program uses a population-weighted random allocation algorithm to assign approximate postal code centroid locations, with an error rate of 1.4%, in Census Metropolitan Areas.[19] These locations were used to spatially match respondents to a mean ambient NO_2 estimate at the DA level. Thus, the DA-level NO_2 mean was calculated as the mean value of all residential NO_2 estimates (point estimates) from all children in each DA. DA-level estimates are, in this sense, weighted by residential locations of the population. Descriptive statistics, such as mean NO_2 values for specific subpopulations, were calculated from this geographically linked dataset. Although household income was used in regression models, mean NO_2 values are provided by income quintile, based on on before-tax income for all households enumerated in the 2006 Census in each city's metropolitan area.

Multiple Ordinary Least Squares (OLS) regression models were used to explore associations between NO_2 air pollution estimates and the variables described above at the DA level. Separate analyses were conducted for each city. Models were fit for all children younger than age 18, and also, for the age groups of infant (0 or 1), child (2 to 12), and adolescent (13 to 17). These age groups were chosen based on preliminary analyses of relationships between age and ambient air pollution exposure in the three cities. In all cities and age group combinations, residuals in the OLS models demonstrated spatial autocorrelation (as indicated by Moran's I statistic); therefore, simultaneous autoregressive (SAR) models were fit concurrently to account for spatial autocorrelation and provide more conservative significance levels for the variables.[20,21] Spatial weights for the SAR model were derived using a Queen's contiguity matrix, which accounts for all neighbouring DAs in creating the spatial weights matrix.[21] Lagrange Multiplier test statistics were used to determine if the spatial lag or spatial error models for SAR would be more appropriate in each case.[21]

Results

Mean NO_2 values across the cities ranged from 19.1 ppb in Montreal to 23.3 ppb in Toronto (Table 1). Mean NO_2 exposure generally rose as household income quintile declined, with children in the lowest quintile having the greatest mean exposure in Toronto and Vancouver (Table 1, Figure 1). In all cities, NO_2 exposure was highest among infants and lowest among adolescents (Table 1). NO_2 exposure of children in lone-parent families and visible minority children generally exceeded city means; the exception was visible minority children in Toronto (Table 1).

Table 1
Mean residential nitrogen dioxide (NO_2) air pollution exposure, by selected socioeconomic characteristics, population aged 0 to 17, Toronto, Vancouver and Montreal, 2006

	Toronto				Vancouver				Montreal			
	Mean NO_2	95% confidence interval			Mean NO_2	95% confidence interval			Mean NO_2	95% confidence interval		
Socioeconomic characteristics	(ppb)	from	to	Number	(ppb)	from	to	Number	(ppb)	from	to	Number
Total aged 0 to 17	23.3	23.2	23.3	119,840	22.0	22.0	22.0	75,730	19.1	19.1	19.2	67,890
Household income quintile												
1 (lowest)	24.1	24.0	24.1	20,480	22.9	22.8	23.0	8,920	19.8	19.7	19.9	9,270
2	23.7	23.7	23.8	25,710	22.8	22.7	22.9	12,550	20.0	19.9	20.1	13,420
3	23.2	23.2	23.3	23,800	22.4	22.3	22.5	14,810	19.5	19.4	19.6	14,680
4	22.9	22.8	22.9	23,640	21.8	21.7	21.8	18,510	18.8	18.8	18.9	13,620
5 (highest)	22.6	22.6	22.6	26,220	21.1	21.1	21.2	20,950	18.0	17.9	18.0	16,890
Age group												
0 to 1	23.7	23.6	23.8	13,010	22.7	22.6	22.8	7,480	19.8	19.7	19.9	7,650
2 to 12	23.2	23.2	23.3	71,510	22.0	22.0	22.0	44,350	19.2	19.1	19.2	40,350
13 to 17	23.2	23.1	23.2	35,330	21.8	21.8	21.9	23,920	18.8	18.7	18.8	19,890
Lone-parent family	23.9	23.8	23.9	24,310	22.6	22.5	22.7	12,800	19.6	19.5	19.6	16,200
Visible minority	23.3	23.3	23.4	68,730	22.8	22.7	22.8	41,020	19.7	19.7	19.8	25,690
Female	23.3	23.2	23.3	57,980	22.0	21.9	22.0	36,690	19.2	19.1	19.2	33,170

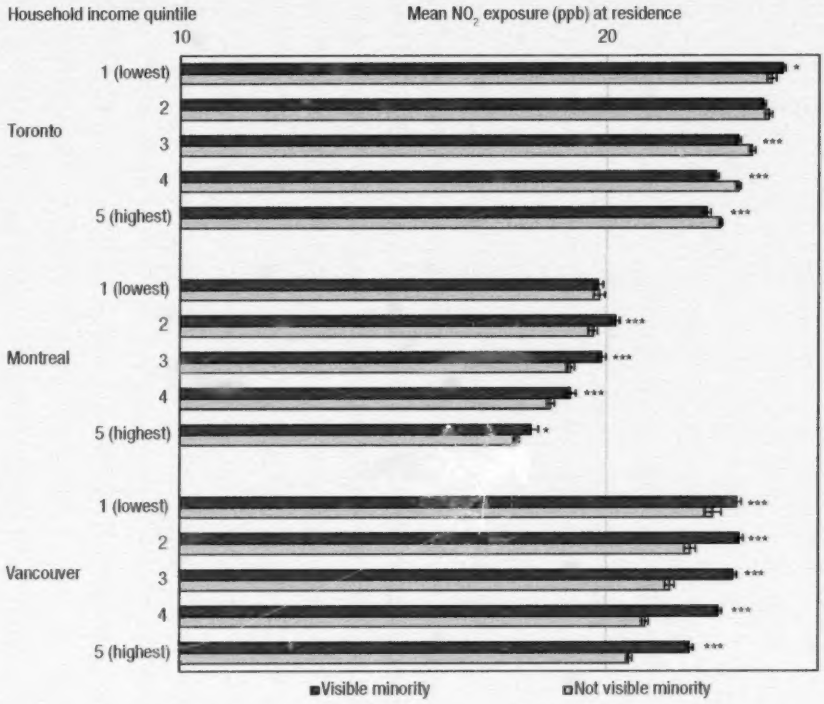
Note: Sample sizes were rounded to nearest multiple of 10 for confidentiality.
Sources: 2006 Census of Canada; Environment Canada, National Air Pollution Surveillance network.

The SAR models were generally similar to the OLS models, but provided more conservative estimates of significance and were a better fit, as evidenced by the greater log-likelihood and lower Akaike Information Criterion values (Tables 2 to 4). In each city, the mean age of children in a DA was negatively associated with ambient air pollution exposure—NO_2 exposure was lower in DAs with older children (Tables 2 to 4). Sex was non-significant in all SAR models (Tables 2 to 4), consistent with the observation that boys' and girls' NO_2 exposure was comparable to city means (Table 1).

Except for one model, air pollution in all cities was negatively associated with increasing household income within a DA in OLS and SAR models (Tables 2 to 4). However, for Montreal, household income in the all-ages SAR model was non-significant ($p = 0.087$), although it was significant in the OLS model and in each age group.

DAs with larger percentages of children in lone-parent families had higher NO_2 exposure in the all-ages models for Toronto and Vancouver. This relationship was also significant for children in the Toronto and Vancouver SAR models, and adolescents in the Vancouver SAR model (Tables 2 and 4). However, in the

Figure 1
Mean residential nitrogen dioxide (NO_2) air pollution exposure, by household income quintile and visible minority status, population aged 0 to 17, Toronto, Vancouver and Montreal, 2006



* significantly different from Not visible minority ($p < 0.05$)
*** significantly different from Not visible minority ($p < 0.001$)
I = 95% confidence interval
Note: Tukey-Kramer post-hoc results are provided for exposure difference between visible minority and white children within each income quintile for each city.
Sources: 2006 Census of Canada; Environment Canada, National Air Pollution Surveillance network.

Table 2
Results of Ordinary Least Squares (OLS) and simultaneous autoregressive (SAR) regression models for associations between selected socioeconomic characteristics and residential exposure to nitrogen dioxide air pollution, by age group, population aged 0 to 17, Toronto Dissemination Areas, 2006

	Total aged 0 to 17				Ages 0 to 1				Ages 2 to 12				Ages 13 to 17			
	n = 4,220				n = 3,446				n = 4,113				n = 4,195			
Model fit	**OLS**		**SAR (lag)**		**OLS**		**SAR (err)**		**OLS**		**SAR (err)**		**OLS**		**SAR (lag)**	
Adjusted R^2	0.073				0.014				0.048				0.042			
Log-likelihood	-11696		-7236		-9717		-6650		-11341		-7127		-11667		-7360	
AIC	23403		14485		19445		13310		22723		14265		23344		14731	
Spatial autocorrelation	**MI**	**z**			**MI**	**z**			**MI**	**z**			**MI**	**z**		
Moran's *I*	0.85	94.35*			0.86	78.74*			0.85	92.65*			0.86	95.61*		
Socioeconomic characteristics	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**
Household income†	-0.86	-7.54*	-0.15	-4.46*	-0.66	-6.67*	-0.15	-4.13*	-0.93	-9.55*	-0.20	-6.05*	-1.00	-8.61*	-0.18	-4.99*
Lone-parent family	3.13	7.99*	0.33	2.77*	0.11	0.40	0.08	0.88	1.80	7.11*	-0.11	-1.40*	2.38	7.02*	0.12	1.12
Visible minority	-1.23	-5.55*	0.11	1.59	-0.72	-4.10*	0.23	3.26*	-0.94	-5.08*	0.19	2.69*	-1.12	-5.34*	0.12	1.88
Female gender	0.42	0.93	0.07	0.48	-0.21	-1.14	-0.11	-1.81	0.08	0.33	-0.04	-0.57	0.46	1.36	0.12	1.16
Age	-0.38	-11.66*	-0.04	-3.72*	...	...	...	...	...	...	...	...	...	...	...	...
Intercept	36.65	26.32*	3.01	6.69*	31.64	27.15*	24.97	46.82*	34.14	29.01*	23.89	39.60*	34.87	24.89*	3.03	6.52*

... not applicable
* significant at $p < 0.05$
† household income log-transformed prior to analysis
AIC = Akaike Information Criterion
MI = Moran's I
Sources: 2006 Census of Canada; Environment Canada, National Air Pollution Surveillance network.

Table 3
Results of Ordinary Least Squares (OLS) and simultaneous autoregression (SAR) regression models for associations between selected socioeconomic characteristics and residential exposure to nitrogen dioxide air pollution, by age group, population aged 0 to 17, Montreal Dissemination Areas, 2006

	Total aged 0 to 17				Ages 0 to 1				Ages 2 to 12				Ages 13 to 17			
	n = 3,126				n = 2,605				n = 3,111				n = 3,005			
Model fit	**OLS**		**SAR (lag)**		**OLS**		**SAR (lag)**		**OLS**		**SAR (lag)**		**OLS**		**SAR (err)**	
Adjusted R^2	0.085				0.022				0.050				0.048			
Log-likelihood	-8827		-6392		-7496		-5777		-8859		-6464		-8529		-6328	
AIC	17665		12898		15003		11602		17728		12977		17069		12667	
Spatial autocorrelation	**MI**	**z**			**MI**	**z**			**MI**	**z**			**MI**	**z**		
Moran's *I*	0.79	77.46*			0.80	64.71*			0.82	79.31*			0.80	75.34*		
Socioeconomic characteristics	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**
Household income†	-0.89	-5.16*	-0.12	-1.71	-0.80	-5.83*	-0.14	-2.18*	-1.23	-7.61*	-0.19	-2.85*	-1.05	-7.48*	-0.14	-2.14*
Lone-parent family	1.72	3.96*	0.28	1.54	0.24	0.67	0.18	1.08	0.83	2.25*	0.11	0.70	0.96	3.33*	<0.01	0.03
Visible minority	1.03	3.21*	0.30	2.25*	0.43	1.86	0.22	2.01*	0.98	3.39*	0.28	2.31*	0.86	3.27*	0.15	1.22
Female gender	0.17	0.34	0.01	0.06	0.01	0.06	0.05	0.48	0.77	1.93	0.23	1.38	-0.05	-0.17	0.06	0.56
Age	-0.43	-10.59*	-0.06	-3.60*	...	...	...	...	...	...	...	...	...	...	...	...
Intercept	32.22	16.01*	3.47	0.86*	28.14	18.20*	3.95	5.29*	32.19	17.08*	3.68	4.53*	30.55	18.63*	21.19	26.70*

... not applicable
* significant at $p < 0.05$
† household income log-transformed prior to analysis
AIC = Akaike Information Criterion
MI = Moran's I
Sources: 2006 Census of Canada; Environment Canada, National Air Pollution Surveillance network.

Table 4
Results of Ordinary Least Squares (OLS) and simultaneous autoregressive (SAR) regression models for associations between selected socioeconomic characteristics and residential exposure to nitrogen dioxide air pollution, by age group, population aged 0 to 17, Vancouver Dissemination Areas, 2006

	Total aged 0 to 17				Ages 0 to 1				Ages 2 to 12				Ages 13 to 17			
	n = 3,067				n = 2,515				n = 3,039				n = 2,942			
Model fit	**OLS**		**SAR (lag)**		**OLS**		**SAR (err)**		**OLS**		**SAR (err)**		**OLS**		**SAR (lag)**	
Adjusted R^2	0.191				0.037				0.119				0.144			
Log-likelihood	-8619		-6088		-7351		-5661		-8658		-6188		-8180		-6163	
AIC	17251		12190		14712		11333		17327		12386		16370		12338	
Spatial autocorrelation	**MI**	**z**			**MI**	**z**			**MI**	**z**			**MI**	**z**		
Moran's *I*	0.76	73.13*			0.81	63.41*			0.81	77.16*			0.74	67.73*		
Socioeconomic characteristics	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**	**coeff.**	**t**	**coeff.**	**z**
Household income†	-1.12	-6.03*	-0.27	-3.67*	-1.04	-7.26*	-0.31	-4.77*	-1.43	-8.02*	-0.27	-3.41*	-1.27	-8.90*	-0.24	-3.72*
Lone-parent family	3.45	6.48*	0.71	3.40*	-0.09	-0.20	0.09	0.52	2.64	5.91*	0.60	3.49*	2.06	6.42*	0.43	2.94*
Visible minority	3.22	11.84*	0.46	4.25*	1.15	5.17*	0.04	0.38	2.80	10.83*	0.64	4.69*	2.87	12.68*	0.50	4.80*
Female gender	-0.38	-0.73	0.28	1.35	-0.20	-0.83	<0.01	-0.03	1.26	3.04*	0.03	0.20	-0.40	-1.35	0.12	0.89
Age	-0.64	-17.02*	-0.06	-4.20*	...	...	...	...	...	...	...	...	...	...	...	...
Intercept	39.19	17.97*	5.34	5.87*	34.23	20.85*	26.38	32.71*	36.41	17.23*	25.44	25.50*	35.14	20.80*	5.06	6.22*

... not applicable
* signficiant at $p < 0.05$
† household income log-transformed prior to analysis
AIC = Akaike Information Criterion
MI = Moran's I
Sources: 2006 Census of Canada; Environment Canada, National Air Pollution Surveillance network.

SAR model, the percentage of children in lone-parent families in a DA was not significantly associated with NO_2 exposure in Montreal (Table 3).

The relationship between household income quintile and air pollution exposure was similar in each city, regardless of visible minority status. In Montreal and Vancouver, however, visible minority children's NO_2 exposure was generally greater than that of children in the same income quintile who were not members of a visible minority; the exception was children in the lowest income quintile in Montreal (Figure 1). In these two cities, DAs with higher percentages of visible minority children had more exposure to ambient NO_2; this significant relationship (in SAR models) was observed among children overall and children aged 2 to 12 in both cities, and among adolescents aged 13 to 17 in Vancouver (Tables 3 and 4). In Toronto, no consistent difference was apparent between visible minority and white children within income quintiles (Figure 1). Similarly, visible minority status was not significant in the Toronto SAR model for children overall (Table 2).

Discussion

In Canada's three largest cities, children in lower income DAs were exposed to more NO_2 than were those in higher income DAs. Additionally, in Toronto and Vancouver, DAs with larger percentages of children in lone-parent families had greater exposure, although the statistical significance of this difference varied by age group. These results support the hypothesis that differences in respiratory health between children of low and high SES may, at least in part, be related to differences in exposure to NO_2.[2] In addition, children in lower income households may be more vulnerable to the effects of air pollution owing to greater innate susceptibility through poor general health or specific health conditions related to low SES.[22] The combination of the effects of exposure and susceptibility to the effects of air pollution among low and high SES adults are difficult to assess quantitatively together.[23] Alternatively, some differences in asthma prevalence between children of low and high SES in previous studies may be explained by other, well-documented contributing factors related to lower SES, namely, lower health services use and greater exposure to second-hand smoke in the home, or earlier use of cigarettes[24,25]—factors not assessed in this analysis.

A secondary finding was that ambient NO_2 exposure decreased within increasing age in each city. This decline in exposure may be related to changes in household SES that influence where families choose to live. In general, household income (while employed) rises over time[26] as children age. As well, home ownership rates increase with parental age.[27] These trends may allow older families to live in more desirable neighbourhoods. Indeed, a study of the three cities found that families with children younger than age 6 moved away from low income neighbourhoods less frequently than did families without young children.[28] Desirable neighbourhoods may be farther from major highways and thoroughfares, and therefore, have lower ambient NO_2 than other parts of the city.

A 2014 national study in the United States found greater exposure to ambient NO_2 among visible minority adults than white adults (4.6 ppb); income was less important.[22] The present analysis showed that children in low income households in each city had greater exposure to NO_2, but the role of visible minority status in exposure differed between cities. In Vancouver, lower income visible minority children were exposed to greater concentrations of NO_2 than were white children in all household income quintiles. The relationship between visible minority status and NO_2 exposure was less clear in Toronto and Montreal. Additional research using a larger sample is necessary to determine differences in exposure among specific visible minority groups.

The disparity in NO_2 exposure between children in the lowest and highest household income quintiles (from 1.5 ppb in Toronto to 1.9 ppb in Montreal) was greater than that observed for the other variables. This within-city disparity is close to that reported for school-aged children Malmö, Sweden, where mean residential exposure to NO_2 ranged from 7.6 ppb in the highest income group to 10.2 ppb in the lowest—a difference of 2.6 ppb.[29]

A 2015 study of adults in the 10 largest Canadian cities found that increments in exposure of 5 ppb in ambient NO_2 were associated with a 5% increased risk of mortality from non-accidental causes and ischemic heart disease, and a 4% increased risk of mortality from respiratory diseases.[15] Given children's potentially greater susceptibility to the effects of air pollution, it is possible that differences of this magnitude may have a measurable effect on health outcomes, such as asthma and other respiratory illnesses. A study of children aged 5 to 9 in Toronto reported associations between NO_2 exposure at birth and the risk of developing asthma and wheeze,[30] although the association was stronger among children with allergic disease.[31]

What is already known on this subject?

- In large Canadian cities, pollution-related health conditions such as asthma tend to be more common among adults and children of lower socioeconomic status (SES) than among those of higher SES.
- In such cities, exposure to ambient air pollution is generally higher among adults of lower SES.
- These differences in exposure to ambient air pollution may account for some of the observed differences in health conditions between these groups.

What does this study add?

- Children in lower income Dissemination Areas (DAs) in the three largest Canadian cities are exposed to higher mean annual concentrations of nitrogen dioxide (NO_2) than are children in higher income DAs—a difference of 1.5 to 1.9 ppb.
- In Toronto and Vancouver, DAs with relatively high percentages of lone-parent families had greater exposure to ambient NO_2.
- In Montreal and Vancouver, DAs with relatively high percentages of visible minority children had greater exposure to ambient NO_2.

Limitations

Despite the significance of the statistical models, the exposure estimates relied on estimates of NO_2 derived from LUR models. Any error introduced during creation of the LUR models, including interpolation error and measurement error (for example, of traffic counts), would be reflected in the point measurements assigned to children in this study. Most of this error was likely mediated by the use of aggregate, rather than individual, point data for the regression models, as well as the use of large samples of children (20% of the population).

Locating the residences of children within the GIS relied on the PCCF+

model, which is highly accurate in urban centres, but does introduce some error through the placement of postal code centroids. Here, residences were mapped by postal code, which is only accurate to the number of residences within each postal code. Use of aggregate (DA) datasets in creating the regression models should mediate some of these errors in locating residences.

The analysis relied on ecological, ambient (outdoor) exposures at a child's residence to assess differences in exposure. However, exposure to air pollution occurs throughout the day in different environments, such as at school, in traffic, and indoors, thereby contributing to misclassification of exposure. Nonetheless, ambient exposure estimates at a person's residence have been regularly used in air pollution research to investigate associations with mortality and other health outcomes.[15,32]

Conclusion

In general, the findings of this analysis support the observation that in major Canadian cities, exposure to traffic-related air pollution is higher among children in lower income than in higher income neighbourhoods, ranging from 1 to 2 ppb. Research on adults suggests that differences in exposure of this magnitude may be medically significant, but additional studies are needed to determine if this translates into differences in health outcomes among children. Future studies of asthma prevalence and respiratory infection hospitalizations among children may be warranted to examine within-city differences in air pollution-related health problems. ■

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